

# Challenges in Large Ground Based telescopes: TMT

Mitchell Troy<sup>a</sup>

*Carl Nissly<sup>a</sup>, Joon Seo<sup>a</sup>*

*<sup>a</sup>Jet Propulsion Laboratory, California Institute of Technology,*

**Workshop on Technology for Direct Detection and Characterization of Exoplanets**  
**Keck Institute for Space Science (KISS) on the Caltech Campus**  
**April 9-12, 2018**

© 2018 California Institute of Technology. Government sponsorship acknowledged.

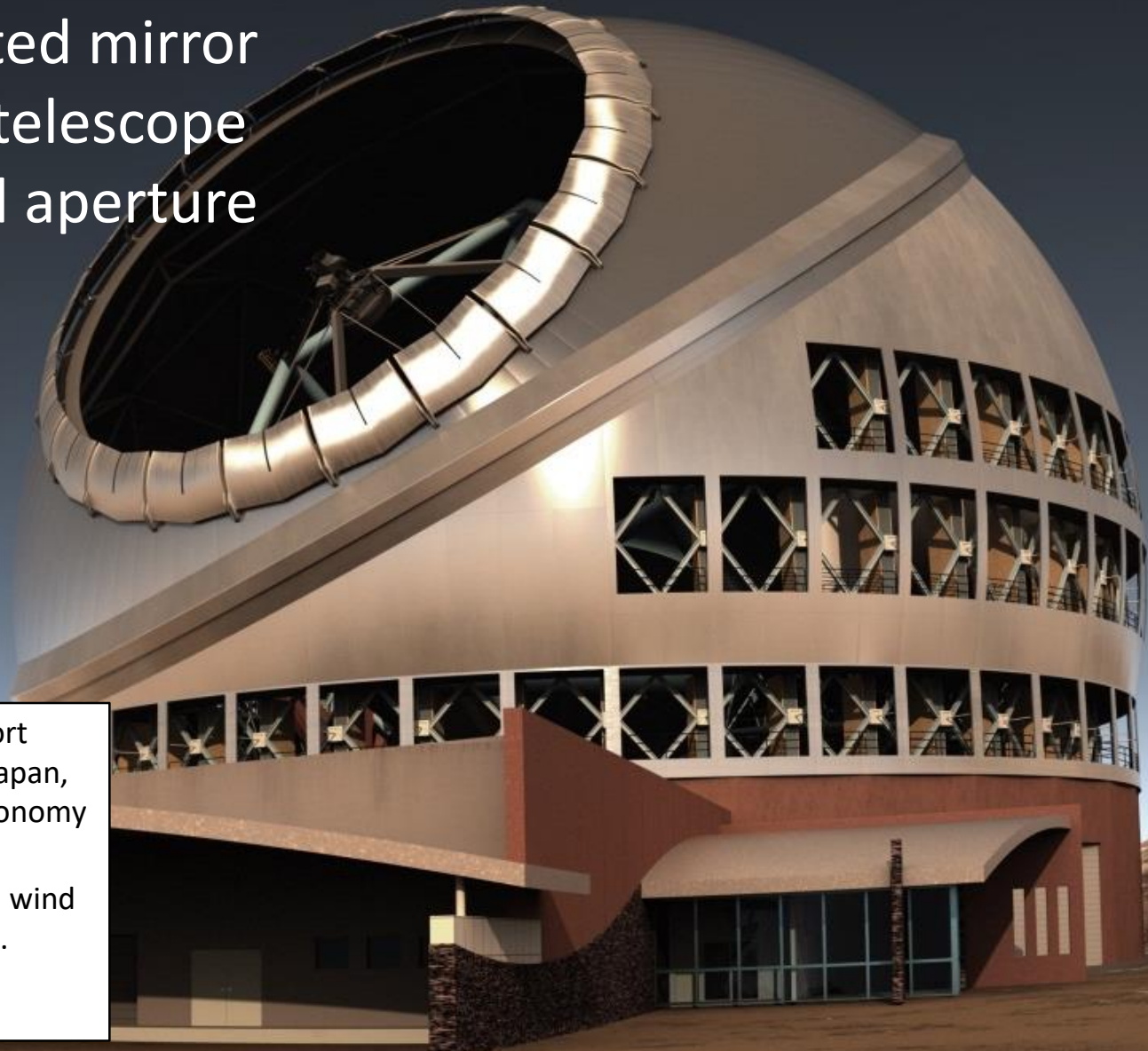
# Outline

- Overview of TMT
- Programmatic Challenges
- Technical Challenges

# Introduction to the TMT Design

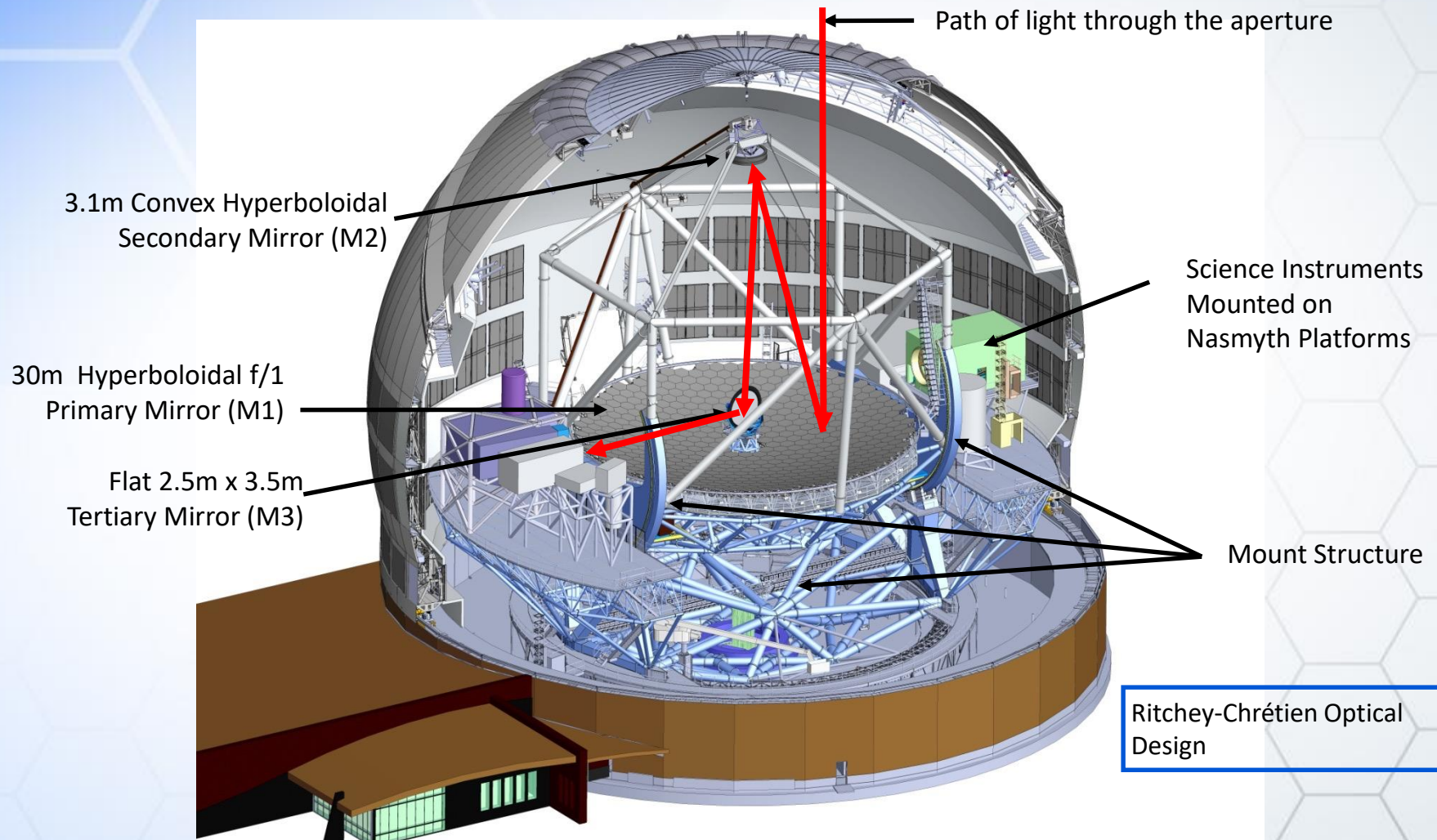
TMT is a segmented mirror  
optical-infrared telescope  
with a 30m filled aperture

- ◆ **Who:** TMT is a collaborative effort between Canada, China, India, Japan, US, and the Caltech and UC astronomy communities
- ◆ **Enclosure:** Calotte for maximum wind protection and at minimum cost. Vents for mirror seeing

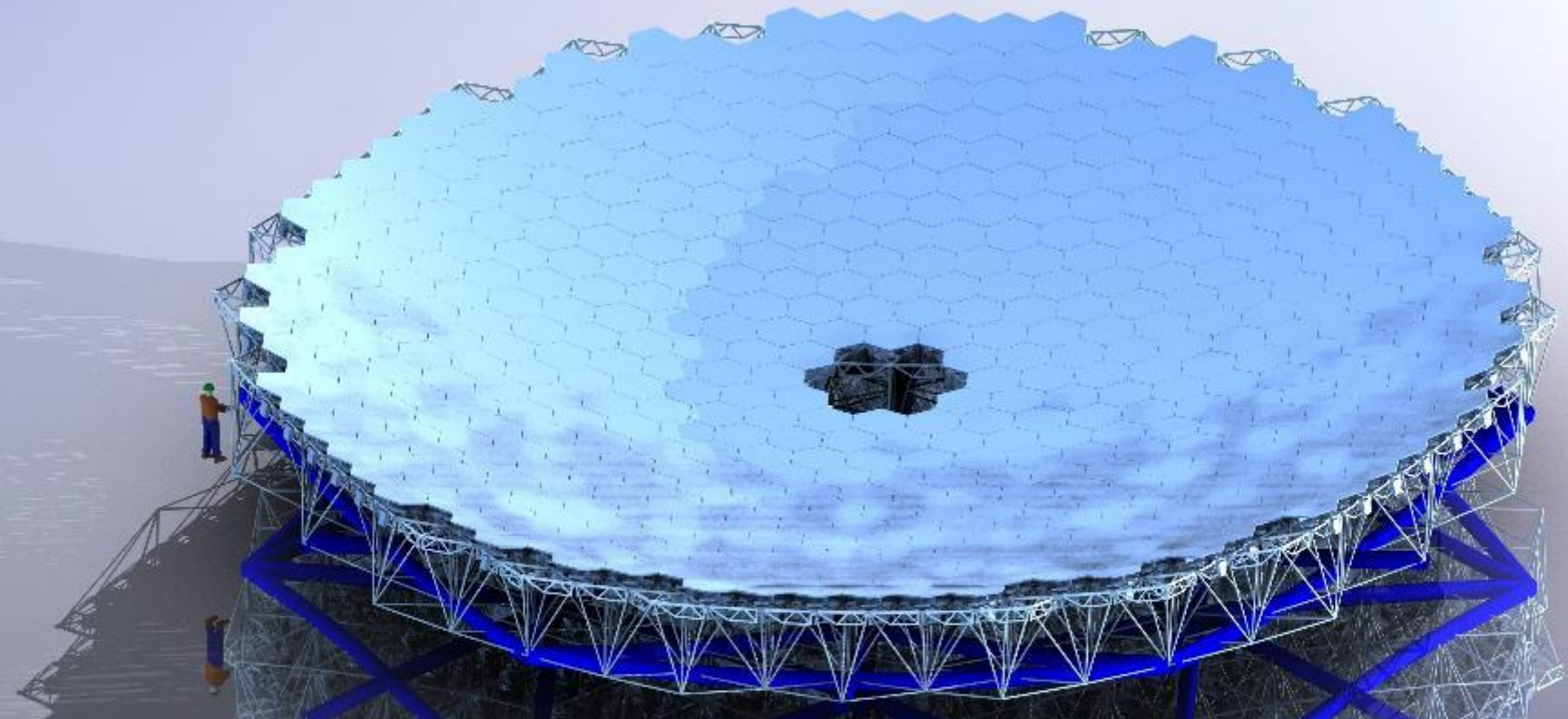




# TMT Telescope Concept Overview



# TMT Primary Mirror (M1)



- ◆ 492 segments
- ◆ 1.44 m across corners
- ◆ 3.5 mm optical gaps between segments
- ◆ 1,473 Degrees of Rigid Body Freedom
- ◆ 21 warping harness's per segment, total of 8,856 Dof.

# Timeline for Science Requirements and Instrument Selection

- ◆ ~2000: CELT Study started
- ◆ 2004: TMT Reference design established
- ◆ ~2005: Science Requirements Document (SRD) released
- ◆ 2006: Instrument feasibility studies
- ◆ 2007: Last “significant” update to SRD
- ◆ 2008: First generation/light instruments selected
- ◆ 2019: 2<sup>nd</sup> generation instrument studies
- ◆ ~2028: First light
- ◆ ~2030: Science operations start



# 1<sup>st</sup> Generation TMT Instruments

- ◆ IRIS - InfraRed Imaging Spectrometer
- ◆ IRMS - InfraRed Multi-Slit Spectrometer (MOSFIRE-TMT)
- ◆ WFOS - Wide-Field Optical Spectrometer

# TMT Programmatic: Similarities to Space

- ◆ TMT and other ELTs are large projects approaching or exceeding space based projects in terms of:
  - ◇ Cost \$1-2B dollar
  - ◇ Complexity
  - ◇ International involvement/collaborators and the associated complexities
  - ◇ Timelines (~25-30 years from first concepts)
- ◆ These projects are also significantly more expensive and complex than previous ground based projects



# Programmatic: Differences from Space

- ◆ Not used to formal system engineering
- ◆ Multiple science goals that cover a wide range:
  - ◇ Seeing limited, diffraction limited, high-contrast
  - ◇ 0.3 to ~30 microns
  - ◇ FoV: ~1 arcsec to ~15 arcmin. A range of ~1000



- ◆ Telescope Design is not optimized for high-contrast imaging or planet detection

# Planet Detection Requirements

- ◆ Exoplanet detection from the ground:
  - ◇ Currently seen as not currently achievable (even with ELTs)
  - ◇ Niche science
- ◆ Result: Requirements development and analysis does not reflect a high priority on exoplanet detection
- ◆ Requirements set in early phases of project
  - ◇ You are going to get what your going to get from the telescope and very little you can do will change the design/requirements in terms of exoplanet detection

# TMT Science Contrast Requirements

**[REQ-0-SRD-0080]** Exoplanets must be detectable at a contrast ratio of  $1e-8$  of the parent star in H-band

Discussion: Requirements will vary from application to application, but the most stringent application is for Extreme Adaptive Optics, used to detect planets around stars. This could be achieved with an AO system with a  $128 \times 128$  DM

**[REQ-0-SRD-0085]** Actual speckle amplitude should be no more than  $1e-7$ .

Discussion: See the PFI instrument requirements for details

**[REQ-0-SRD-0090]** Prior to AO, individual segment wavefront errors should be no more than about 20 nm rms.

Discussion: Individual segment surface smoothness and accuracy is critical to achieve [REQ-0-SRD-0085].

# TMT Science Contrast Requirements

## "Achievable contrast with coronagraph"

**[REQ-0-SRD-1525]** The system should reach planet detection sensitivity of  $10^8$  before systematic errors dominate. This should be achieved in H band on stars with  $I < 8$  mag and at working distances of 50 mas. The goal is  $10^9$ .

**[REQ-0-SRD-1530]** For younger, distant, dusty stars (such as Taurus) may require IR WFS but have brighter planets, so the goal is planet detection sensitivity of  $10^6$  with  $H < 10$  at inner working angles of 30mas, with a goal of  $5 \times 10^6$ .

Discussion: Contrast is defined as the  $5\text{-}\sigma$  ratio of primary star brightness to the residual speckle and photon noise, i.e., the spatial standard deviation of the final intensity of the PSF halo in a small region.

Discussion: Speckles are expected to be the major background limiting reliable planet detection. Speckle amplitude is defined (for TMT) as the  $5\text{-}\sigma$  amplitude of speckle brightness.

It is expected that suitable data gathering methods and data reduction methods will allow reliable planet detection to take place at 1/10 of the speckle amplitude. Thus, the actual telescope quality should be such that contrasts 10x smaller than the above numbers should be produced by the telescope and PFI system, prior to data reduction.



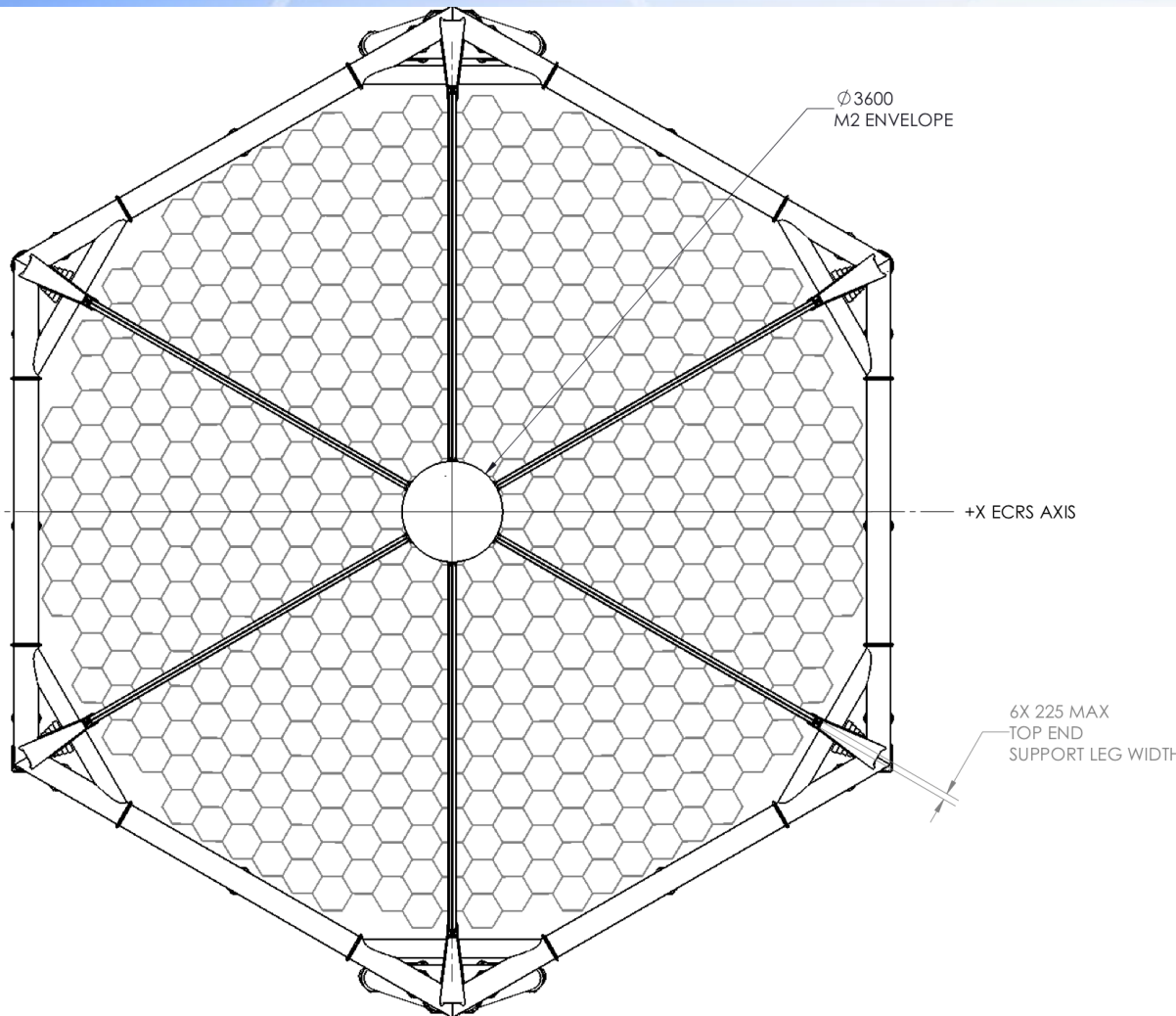
# Technical Challenges

- ◆ Pupil and/or field rotation
- ◆ Reflectivity variations from optics
- ◆ Obscuration not optimized for high-contrast imaging
- ◆ Optical Wavefront Errors
  - ◇ Alignment (segment tip/tilt/piston)
  - ◇ Residual segment figure
  - ◇ Thermal
  - ◇ Gravity
  - ◇ *Segment edges*

# Reflectivity variations from optics

- ◆ The SRD specifies that the M1 segment reflectivity's should be better than 99% at wavelengths longer than 1.5 microns
- ◆ The baseline segment replace scenario is ~10 segments every 2 weeks.
  - ◇ This implies an average segment will be recoated every ~ 1 year
- ◆ A mean segment reflectivity of 99% with a 1% variation results in a contrast of  $\sim 1.3E-7$  from 3 to  $10 \lambda/D$ 
  - ◇ This is a significant error term as large as the impact from phase errors
- ◆ Solutions will be required. The most likely seems to be to use multiple deformable mirrors to correct the amplitude and phase errors

# Obscuration Not Optimized for High-Contrast Imaging



central obscuration

12 support legs

ports will “segment” the  
then using Extreme AO

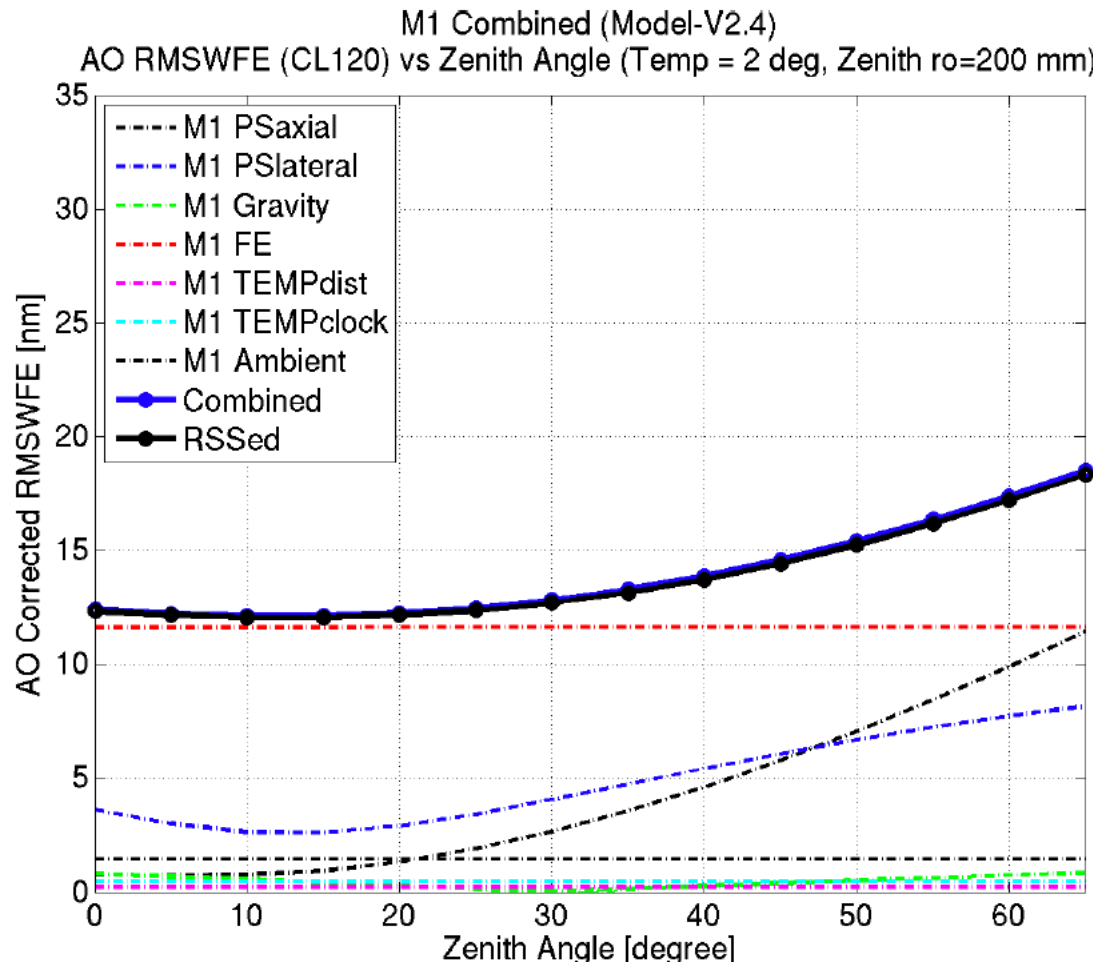
likely introducing wavefront  
distortion errors

gaps between segments are

typical gaps 3.5mm

diffraction suppression  
required

# M1 Residual Figure Errors Post 120<sup>2</sup> AO control

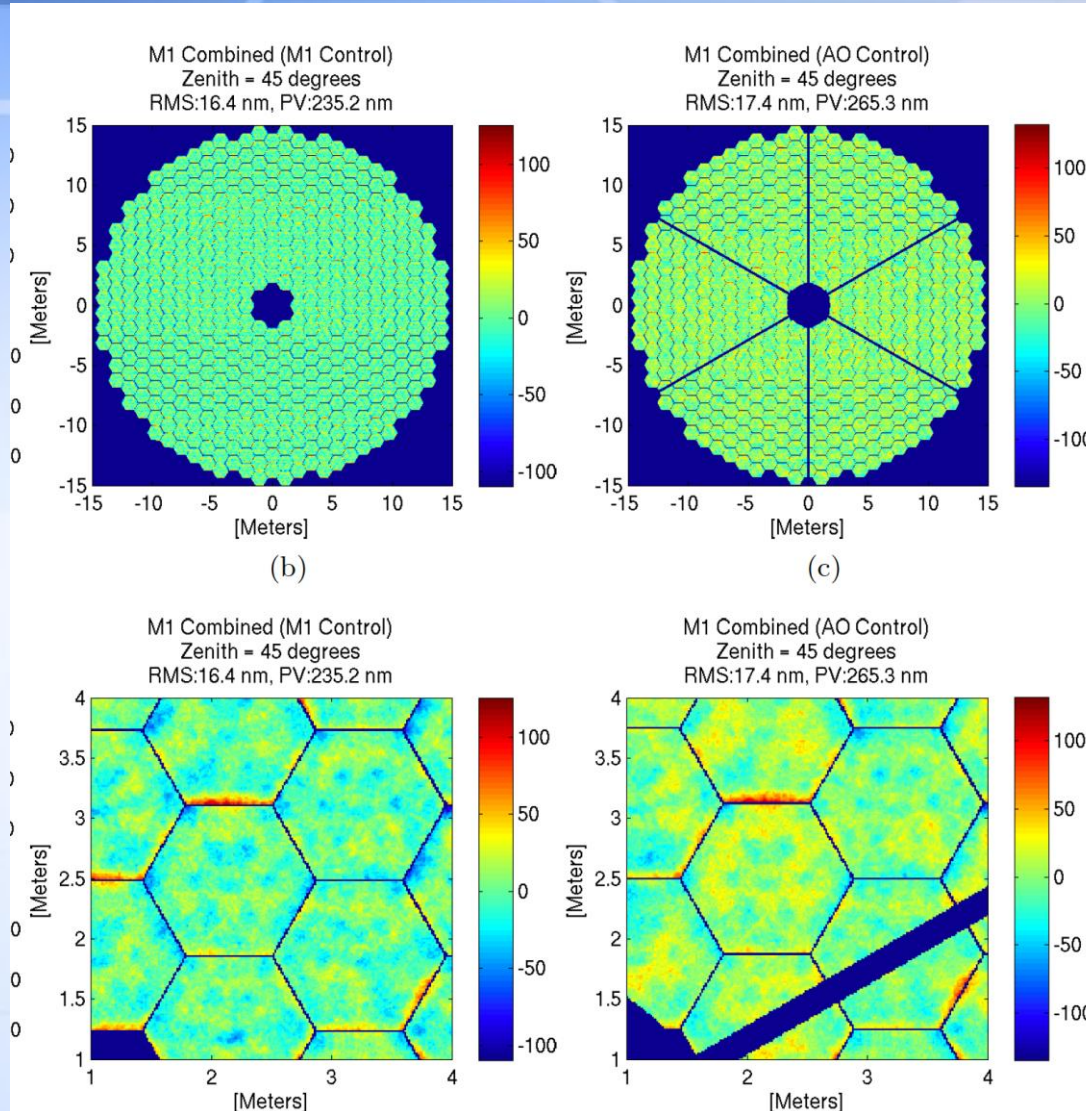


- Residual M1 Figuring Error is dominate error term
- Gravity errors from segment support (PSaxial and PSlateral) are significant at larger zenith angles



# M1 Residual Figure Errors: Phase Maps

## Post 60<sup>2</sup> AO Control



- ◆ ~17 nm RMS OPD
  - ◇ 1st generation AO (NFIRAOS) does not significantly improve errors
- ◆ 120<sup>2</sup> AO reduces errors to ~12 nm RMS OPD
- ◆ Edge effects from control are significant

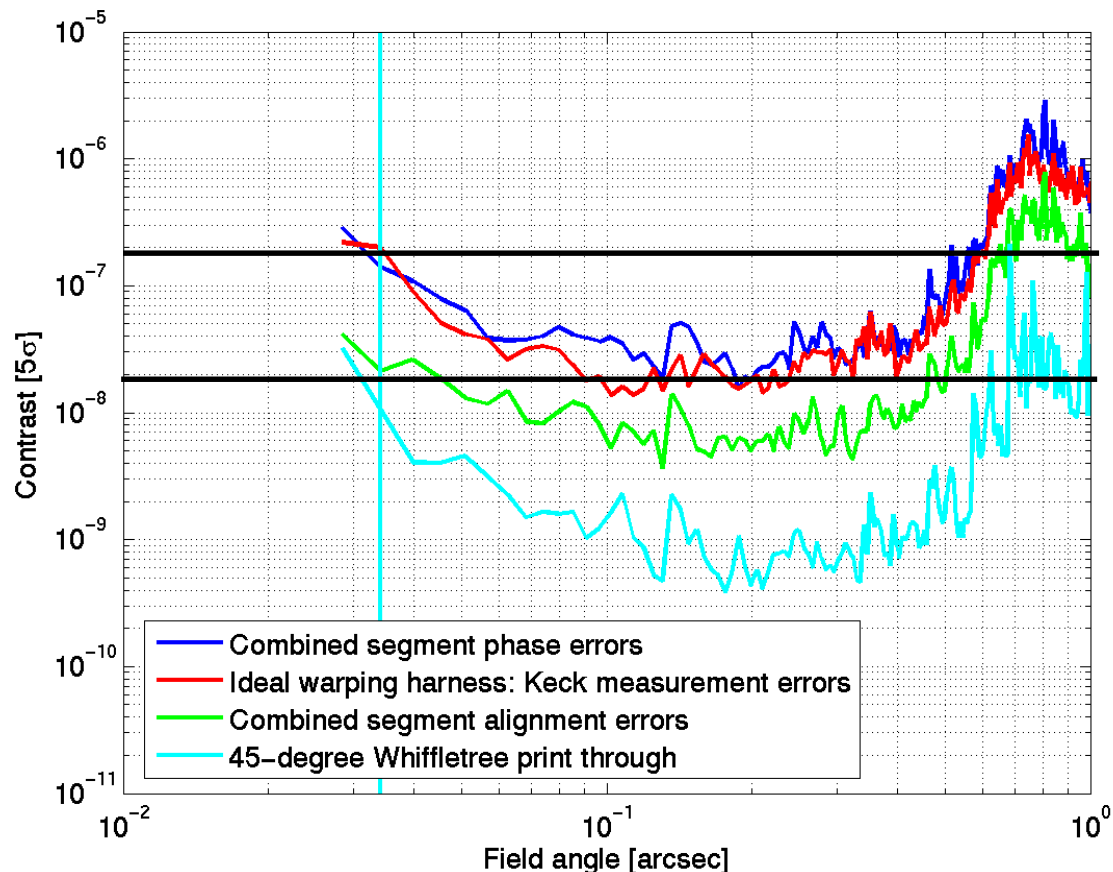
# 2006 Feasibility Design study for a “Planet Formation Instrument for TMT”

- ◆ Investigated the impact of telescope aberrations on contrast
- ◆ Relevant conclusions from that study:
  - The telescope will not limit contrast at the  $10^{-8}$  level
  - The relatively small segment gaps do not limit contrast, but the larger obscurations from M2 and its supports are challenging
  - Segment-to-segment reflectivity variations are an issue
    - ◆ Will require amplitude control using a 2nd DM
  - Segment phasing and telescope alignment in general is not a driver in the performance
    - ◆ 5 sigma contrast at  $3 \lambda/D$ :  $\sim 2 \times 10^{-8}$
  - Residual segment aberrations are a key driver in the performance
    - ◆ 5 sigma contrast at  $3 \lambda/D$ :  $\sim 2 \times 10^{-7}$

# Wavefront Error Table

	RMS (2006) (nm Wavefront)		RMS (2016) (nm Wavefront)	
	Pre-AO	Post-AO	Pre-AO	Post-AO
Segment Aberrations Ideal correction with Keck Meas. Errors	17.3	9.1	12.8	~13
Whiffletree print through	12.2	11.4	17.6	~16
Segment piston	12.7	4.5	13.6	~4
Segment tip/tilt	8.3	3.8	190	~5
<b>Combined errors</b>	23.2	<b>14.6</b>	192	<b>22</b>

# Contrast From All M1 Phase Errors



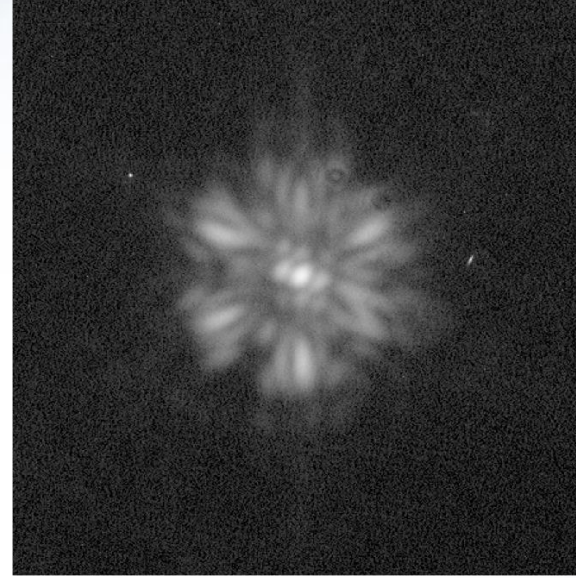
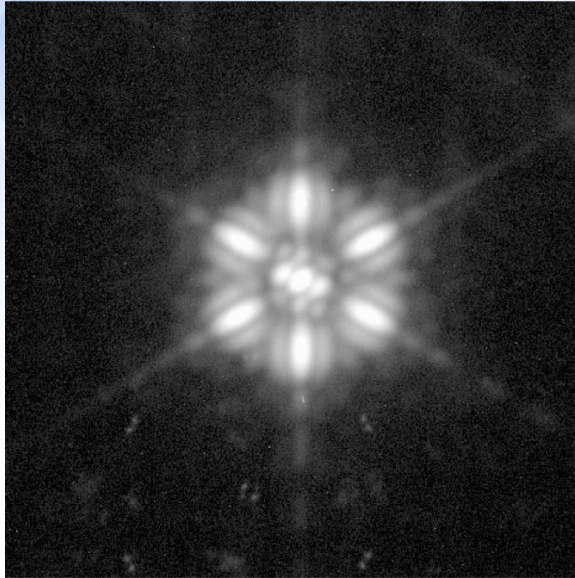
- Phase errors are dominated by residual segment aberrations
- Contrast is:
  - $1.4 \times 10^{-7}$  at  $3\lambda/D$
  - $5.6 \times 10^{-8}$  from 3 to  $10\lambda/D$



# Segment Edge Artifacts (From a working telescope)

- ◆ Keck segments appear to suffer from small but significant surface artifacts near the edges (60-100mm) that:
  - ◇ Place limits on phasing accuracy by creating a chromatic effect.
  - ◇ Directly impact image quality due to light diffracted at angles larger than  $\pm 3.5$  arcseconds from the edges.
- ◆ These effects are likely caused by IBF residuals with a spatial period of 1-3 cm and 10-20 nm amplitude.
  - ◇ Measurements of the Keck segments with an interferometer are currently being planned.

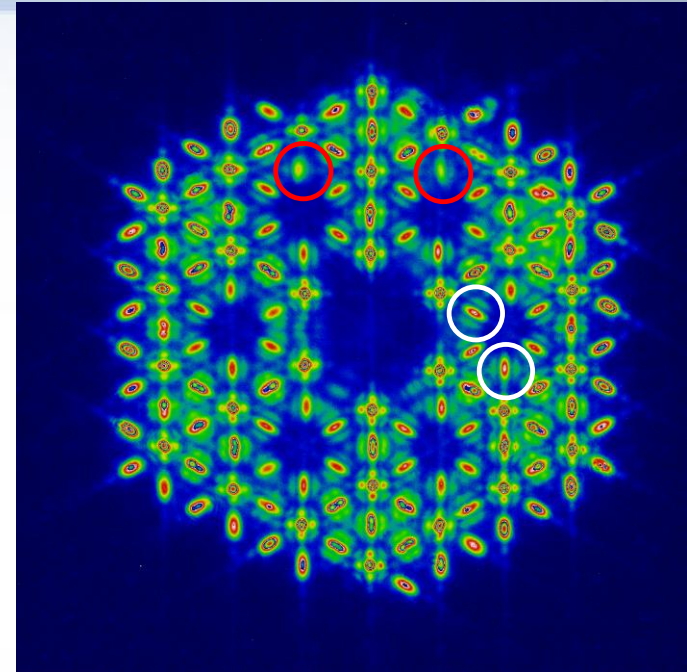
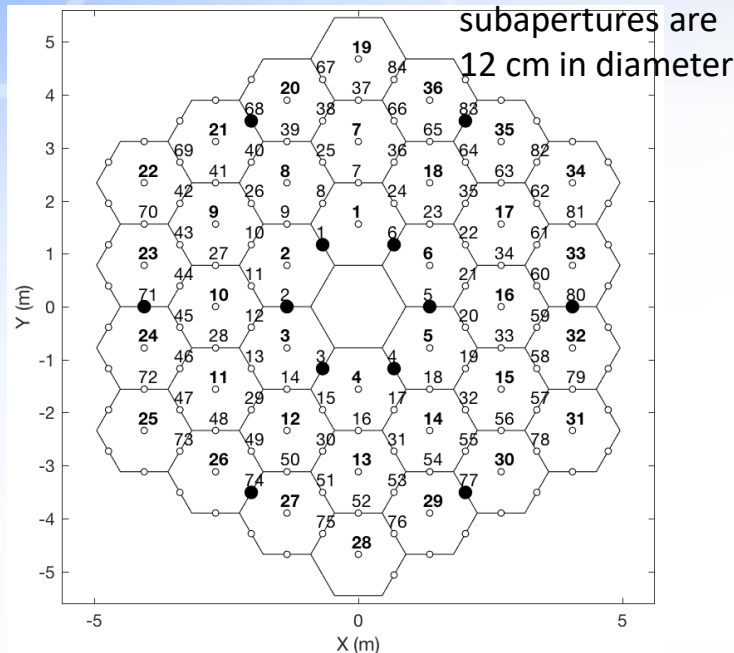
# Scattered Light From Edges Single Segment



- Images are diffraction patterns formed by light from single segments passing through the phasing camera optics with the phasing mask.
- On the left a good segment and on the right one of the worst segments (SP14/SN09).

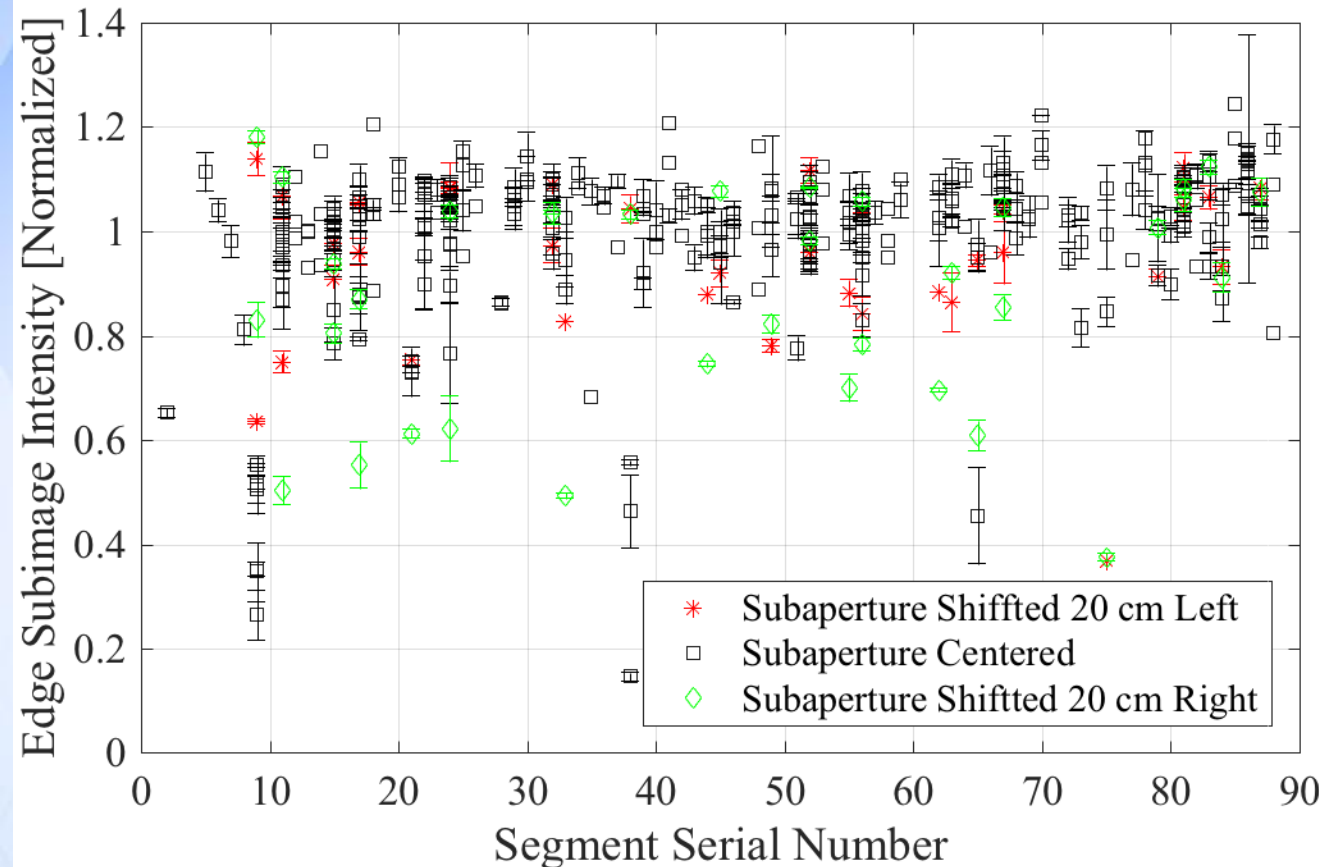
# Scattered Light From Edges

## A Systematic Evaluation



- Photometry from a segment edge over a 6 cm semi-circle can be measured using the above subaperture mask and tilting segments out of the stack.
- The two red circles highlight subapertures on segments (SP) 20 and 36 that clearly have lower flux than those (circled in white) on SP 6 and 15.

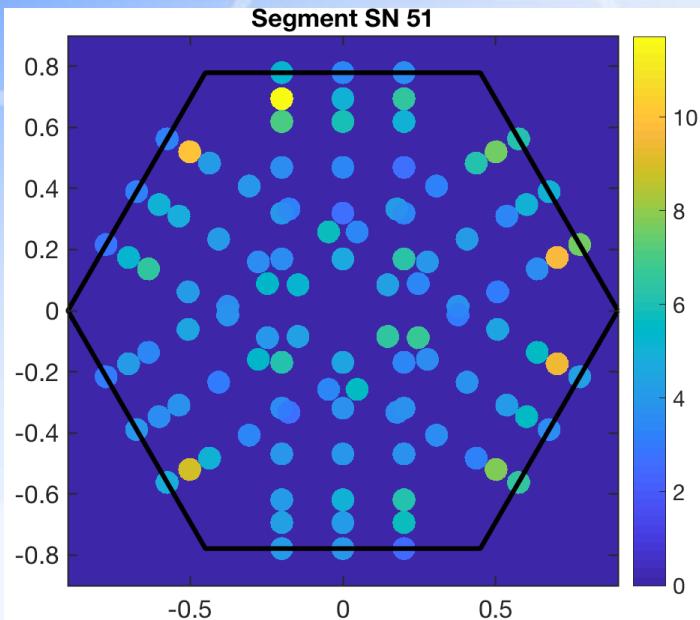
# Scattered Light From Edges A Systematic Evaluation



- 25% of segments have edges with a significant reduction ( $> 20\%$ ) in intensity within  $\pm 3.5$  arcseconds.



# Preliminary Results From Measurements of Keck segments with an Interferometer



- The predicted TMT residual AO (120CL) M1 surface errors are 6nm RMS surface
- The proposed TMT requirement for these spatial frequencies is ~5 nm RMS surface
- Artifacts from IBF support pads are excluded from the RMS surface error calculations

- RMS surface errors over the 15 cm interferometric phase measurement

- ◊ Zernike orders 1 and 2 removed

# Segment Edge Summary

- Stress Mirror Polishing (SMP) was designed to NOT introduce edge effects
  - ◊ Ion Beam Polishing (IBF) post SMP however, can introduce edge effects at these 1-3 cm spatial frequencies
- Other mirror polishing techniques such as those used for segments for space telescopes will also likely introduce edge effects
- If the ELT segments are similar to the Keck segments it would reduce the H-band Strehl by  $\sim 5\%$  and have a significant impact on contrast

# Summary and Conclusions Related to Planet Detections

- ◆ There are many similarities in the challenges ground and space telescopes face
- ◆ At TMT it will be difficult to change the telescope requirements based on those for planet detection
- ◆ Instrument/Science teams need to work with TMT to understand how the telescope design will impact performance
  - ◇ The specific science instrument designs (wavelength, diffraction system) and science case need to be evaluated.
- ◆ The TMT PFI study showed that
  - ◇ The telescope alignment errors are not a significant source of error
  - ◇ Residual segment aberrations are a significant concern
- ◆ Segment “edge” effects need to be understood and evaluated.

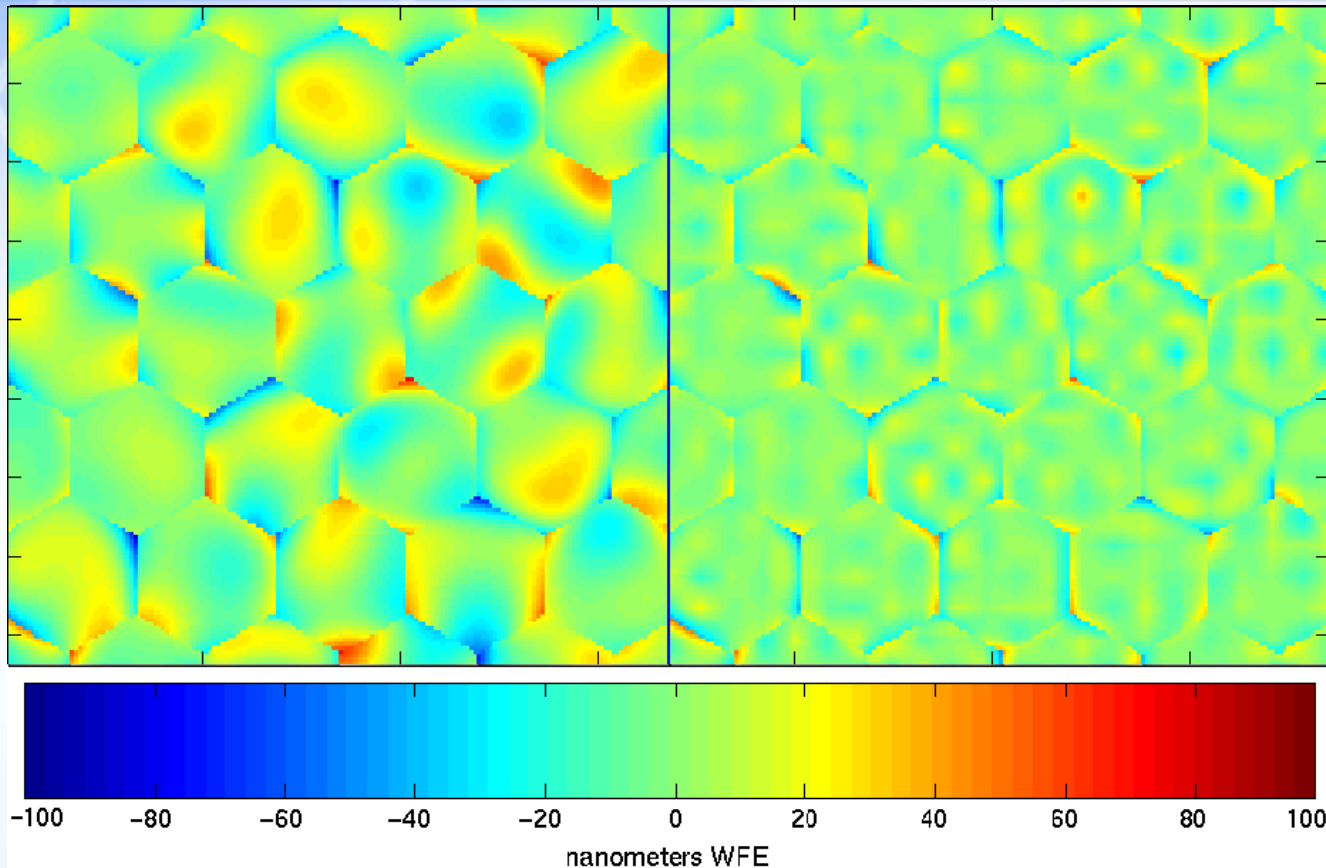
# Acknowledgements

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the California Institute of Technology and the National Aeronautics and Space Administration. The TMT Project gratefully acknowledges the support of the TMT collaborating institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology, the University of California, the National Astronomical Observatory of Japan, the National Astronomical Observatories of China and their consortium partners, and the Department of Science and Technology of India and their supported institutes. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.



# Backups

# Segment Aberrations Before and After AO



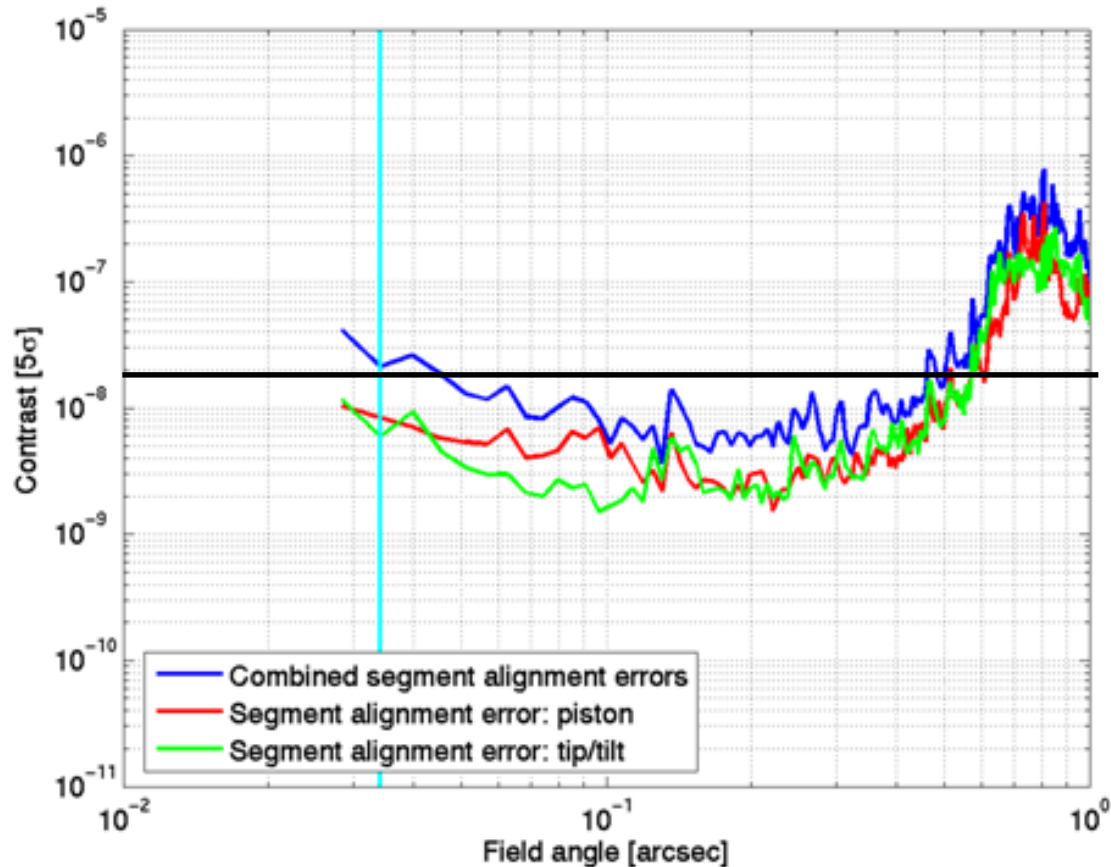
◆ RMS: 17.3 nm

◆ P-V: 242 nm

◆ RMS: 9.1 nm

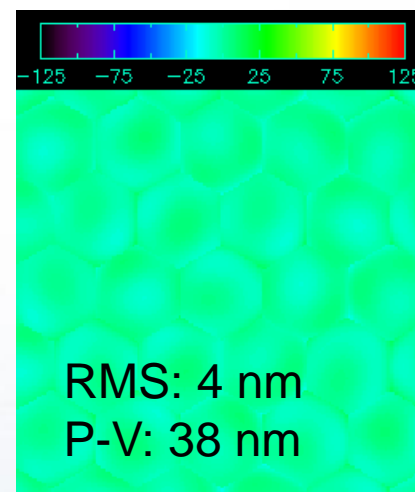
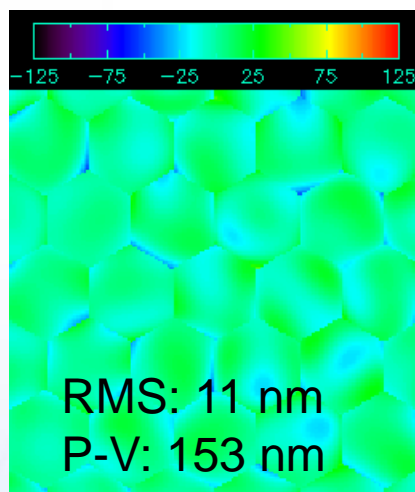
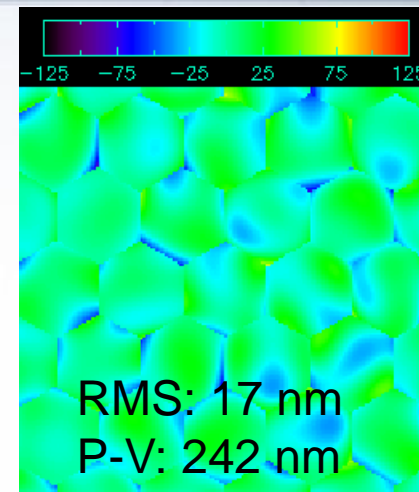
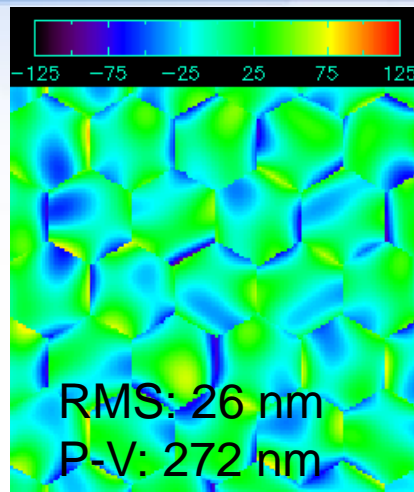
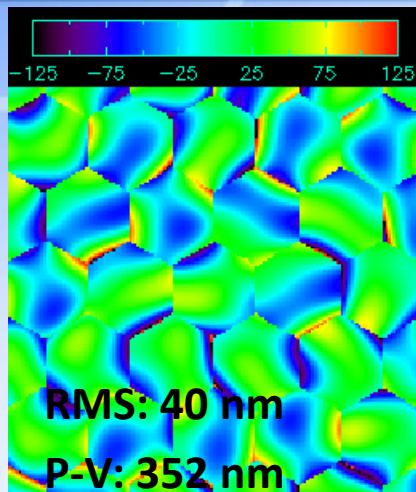
◆ P-V: 199 nm

# Contrast From Segment Alignment Errors



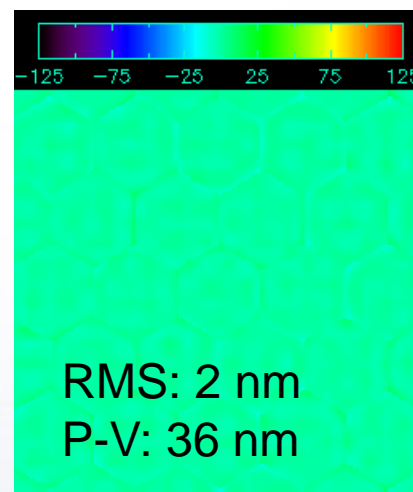
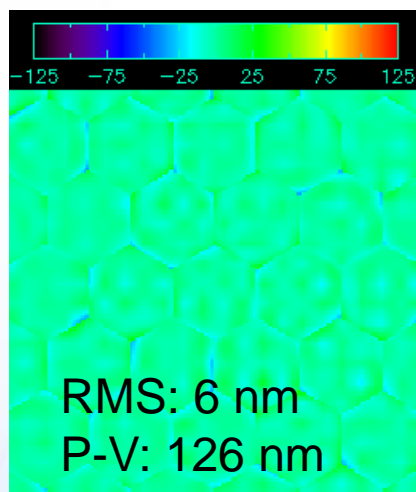
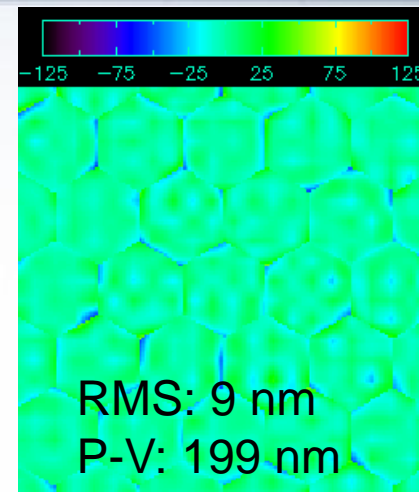
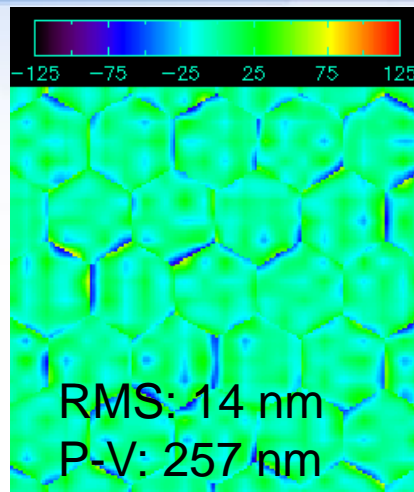
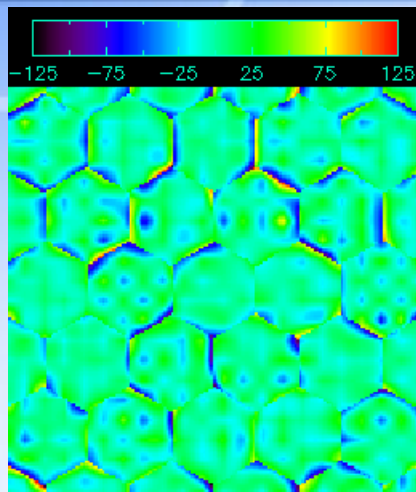
- Segment piston and residual tip/tilt errors are about equal in magnitude

# Various Segment Aberrations





# TMT AO Corrected Segment Aberrations



# Contrast Versus Segment Aberrations Assumptions

